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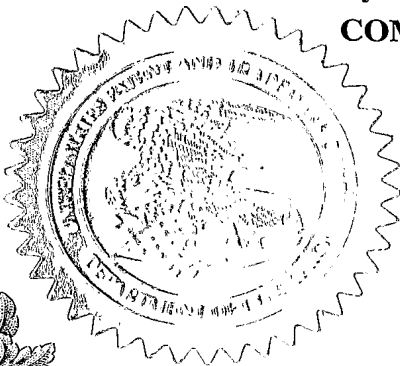
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**APPLICATION NUMBER: 60/540,141**

**FILING DATE: January 29, 2004**

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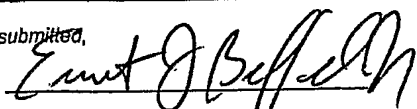
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Additional inventors are being named on the _____ 1 _____ separately numbered sheets attached hereto						
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Respectfully submitted,

SIGNATURE



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Date 29 January 2004

REGISTRATION NO. 43,489

(if appropriate)

Docket Number: MLSE 1040-1

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Docket Number **MLSE 1040-1**

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**MICRONIC LASER SYSTEMS****Registration calibration**

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**Report**

Utfärdare / Issued by <b>Peter Ekberg and Lars Stibler</b>		Datum / Date <b>2003 07 02</b>	Filnamn <b>191</b> / File Name <b>timeToImage.doc</b>	Ersätter / Replace
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## Summary

The method used for measuring time in a deflector system has been used many years. Almost no modifications in the algorithm have been done so far. Only the pattern used for different kinds of calibrations has been modified during the years. Today we have an experimental verified repeatability of the method in the range of 10-15 nm over a surface of 800x800 mm. The 10-15 nm means here the measurement overlay.

One drawback of the method used is that we so far only can measure in the same direction as the micro sweep. In order to measure an X-coordinate we therefore must use special patterns containing 45-degree bars.

This report will suggest how current method can be extended so that we can measure on any kind of pattern. By doing this modification we therefore can generate an image of the pattern without using any other detection method than the one we already are using today. Another nice thing is that no new hardware is needed since everything that is done in software.

## Current method

Before we go in to the actual extension of the algorithm we should recapitulate how current method works. This is important since the extension if the method works similar but 90 degrees rotated.

To measure time with high accuracy is difficult. If for an example you want to measure a pulse with the resolution of 1 ns you need a measurement clock with the frequency of 1 GHz if classical frequency measurement methods are used. In our case we never need to measure a single shot of a pulse. Since we use a scanning beam when we measure we will get several one-dimensional images of a bar or several bars, as an example. We are only interesting in the "average" position of an edge or the CD of a bar. The measurement system will only give an average result together with its sigma. It is important to remember that the measurement system is good enough if this sigma is lower than the natural noise in the system. This natural noise can be summarized to be laser noise, electronically noise and mechanical noise. The noise from the measurement system itself can be calculated theoretically or verified in practice with a known reference signal. It is also possible to get a figure of the measurement system noise by simulation. The measurement of the position of the bar or the CD will therefore contain the error:  $\text{Error}_{\text{tot}} = \sqrt{\text{Error}_{\text{natural}}^2 + \text{Error}_{\text{measurement}}^2}$ .

### The random phase method.

When we measure time we use a so-called random phase method. What this means is that the measurement unit it-self is completely un-correlated in phase to the signal we want to measure. Due to the fact that the signal phase is random relative the



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measurement clock phase we can use a measurement clock frequency that is much lower and use an "averaging" effect instead to achieve the accuracy.



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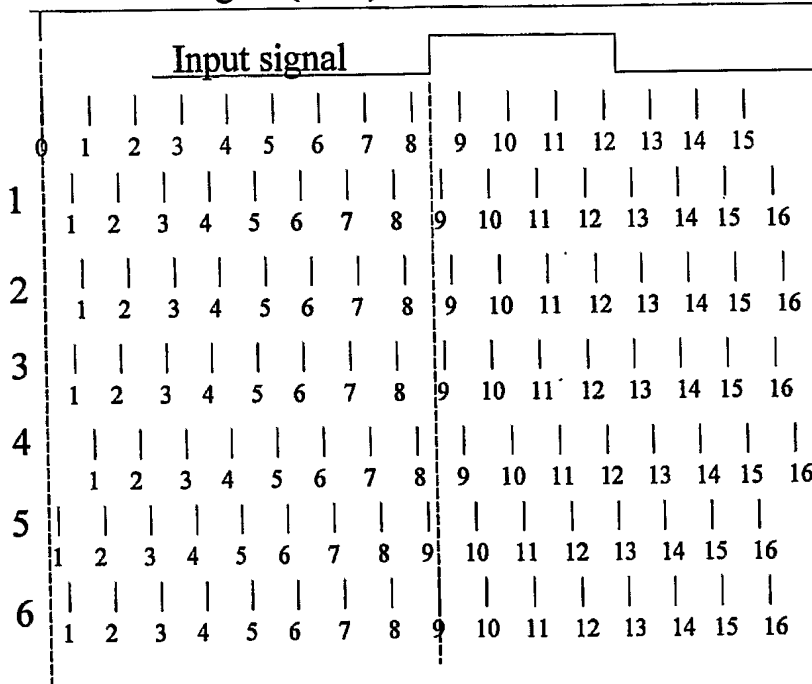
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In the figure below the measurement clock phase is shown relative the reference signal. Please note that the input signal (the bar) is synchronized with the reference signal since it is generated from the micro sweep itself. The red clocks in the figure are the ruler marked in measuring clock increments. What we are after is where the positive going edge of the input signal is relative our reference. Of course we also are interested of the negative going edge. But the same method may be used to find the position of any edge.

**Reference signal (SOS)**



Now we shall introduce some terms. Let us call the period time of the measurement clock  $tm$ . Since the input signal is a result from the micro sweep we also know exactly the relationship between the pixel clock period in time and what that corresponds to in nano meters. Here we introduce  $tp$  for the pixel clock period in nano seconds. We also call the pixel clock period in nanometers for  $pp$ . The scaling expression can therefore be expressed as:

$$pm(nm) = pp(nm)/tp(ns) * tm(ns).$$

$pm$  is what each measurement clock period corresponds to in nano meters. From the figure above we can see that the approximate position of the first edge is 8 pixel clocks. Please note that by doing only one measurement i.e using one of the six measurements we can see that the edge is within the range of 8 - 10 measurement clocks. The accuracy is



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in other words  $2 \cdot t_m$ . Using above scaling expression this can be expressed in nano meters to.

We now introduce some realistic numbers. This numbers is taken from the TFT3 system parameters.

$$t_m = (1/40) = 25 \text{ ns.}$$

$$t_p = (1/46,7) = 21.413 \text{ ns.}$$

$$p_p = 250 \text{ nm.}$$

This leads to that the  $p_m = 291.86 \text{ nm.}$

If we now count measurement clock ticks by resetting a counter by the reference signal we see that we only will count 8 or 9 ticks. No other count is possible in this example. The edge position relative the phase of the measurement clock wills in this way be rectangular distributed inside  $t_m$ . The average position can therefore be calculated just by adding counts from several measurements together and divide this number with number of measurements. In this example we get  $(8+8+8+8+9+9)/6 = 8.33$  counts as an average value. So an estimation of the position of the edge can be calculated to be:  
 $8.33 \times 291.86 = 2432 \text{ nm.}$

Now it is not enough just to use 6 measurements as in this example. Normally you use several thousands of measurements. (In the appendix the three sigma of the average value is described from a theoretical point of view.)

## Two-dimensional measurements.

So far we only have used this method to measure along the micro sweep i.e. in one dimension. It is though possible to extend the method to measure in two dimensions. When we do this we actually are generating images of the pattern we measure. When we talk about images we normally see this as a set of pixels. (Each pixel has a certain "gray-level" that describes the intensity of the pixel). When handling CCD images each pixel is fixed in position in a certain raster (or grid). When analyzing a CCD image for finding the position of an edge both information of the pixels location and gray-level must be used. Different straightforward methods may be used for estimating an edge position in the image. The accuracy of the position estimation depends in the calibration of the CCD array i.e. where the pixels are located in the array, how sensible they are for light and how well we can place the image on the array without any distortions. Light distribution over the CCD and different kinds of optical distortions will contribute to the error of the position estimation. A lot of these errors can be overcome if we calibrate the measurement system against a known reference.

When using this suggested method we also can talk about pixels. But our pixels are not fixed in location in a certain grid. If we make a "snap shot" of the pattern by just measuring it once we will get information with a quite rough resolution (or accuracy). It is important to realize that the only information we are using is the pixels location. We





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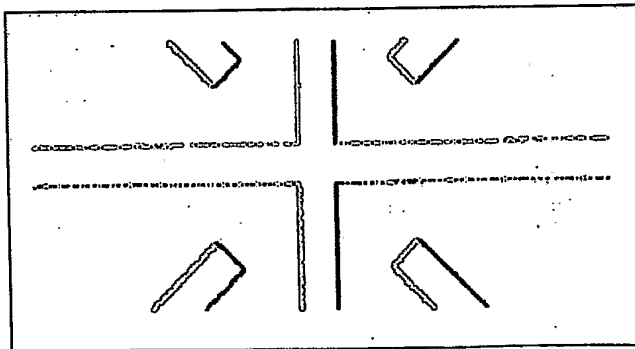
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do not use any gray-level information at all. Of course it is possible also to use gray-level information by recording the pattern using different "trig" levels in the hardware. This is what we do if we are interested in beam-shapes as in focus measurements. Here we only are interested in measuring the location of one or several bars so we can calculate center of gravity and CD.

When measuring registration and CD we never are interested in the exact location of one single pixel. Normally we only are interested in the average of several pixels location. In a CD measurement we use cursors to define number of pixels to be used in this average value. Also in the center of gravity estimation we use cursors to "even out" noise from the edge. This noise might be roughness from the pattern itself or noise in the measurement system. This is the same when using a CCD image as input. In this suggested method we use the micro sweep itself as our light source (or ruler). It is hard to find a more accurate ruler than this. We already have methods to calibrate this ruler both in power and linearity very accurately.

In next picture we have grabbed an image of a part of our star-mark. The image shows the location of pixels in a grid of (316x250) nm. Nothing more than just showing the pixels in this grid has been done in the image.



The image shows so called events in the area. The mark has been scanned with a hardware cursor of 100  $\mu\text{m}$ . The positive going edges are shown as white pixels and negative going edges (chrome-glass transitions) are shown as black pixels. Just by observing this image you can see that the mark is slightly rotated counter clock vice. The number of black pixels in the lower Y-parallel bars compared to whites ones is a clear indication of this fact.

In order to demonstrate the actual grid we are using and how the pixels are distributed in this grid we shall look in the next picture.



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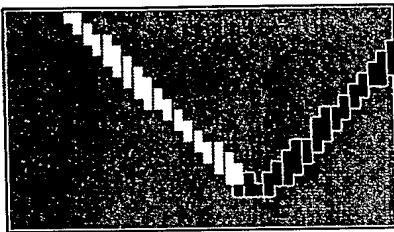
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Here we have enlarged a part of the image. This "hard copy" of the image shows clearly where we have found events. The method to "sharpen" up this image will be presented in next section in this report. The scale in this image is correct in that sense that one pixel is 316 nm in X-direction (vertical scale) and 250 nm in Y-direction (horizontal scale).

### Estimation of the X-coordinate.

As has been described earlier we have a very accurate method to estimate the Y-coordinate of an event. We use the micro sweep as a ruler and a measuring clock that is random in phase relative the ruler. The measurement clock will give us a rough resolution of  $tm$  (292 nm) in a single shot measurement. If we use several measurements and build us an average value we will get a much higher resolution (see appendix). Actually we can choose the accuracy just by selecting number of measurements and the length of the cursor to be used. So far this is true for the estimation of the Y-coordinate. So! How do we do to estimate the X-coordinate?

Obviously it is difficult to believe that it is possible to get an X-value out from data retrieved by a scanning a beam in Y-direction. The big step forwards is that it actually is possible to retrieve this information almost with the same accuracy as the Y-coordinate. But to get it we must introduce another signal (that actually already is used), the  $\lambda/2$  X-signal.

When measuring a 45-degree bar of a pattern as in the star-mark case we use the  $\lambda/2$  signal as "marks" in X-direction to define a X-cursor. Inside the cursor we also record the  $\lambda/2$  signal simultaneously when we count the measurement clocks. But since we measure on a 45-degree bar we actually are using only Y-information to get the X-coordinate. In combination with the  $\lambda/2$  information we can calculate the X-coordinate with a very high accuracy. The drawback of this method is of course that we are not able to measure on any kind of pattern. Especially we cannot measure on a bar that is parallel with the ruler. If we extend the method we already is using in Y-direction a little bit, we will soon realize that the problem to solve is exactly the same as we have in Y-direction but rotated 90 degrees. If we change our measurement clock to our reference signal (here the SOS) and use the  $\lambda/2$  signal as reference instead we have rotated the problem 90 degrees.

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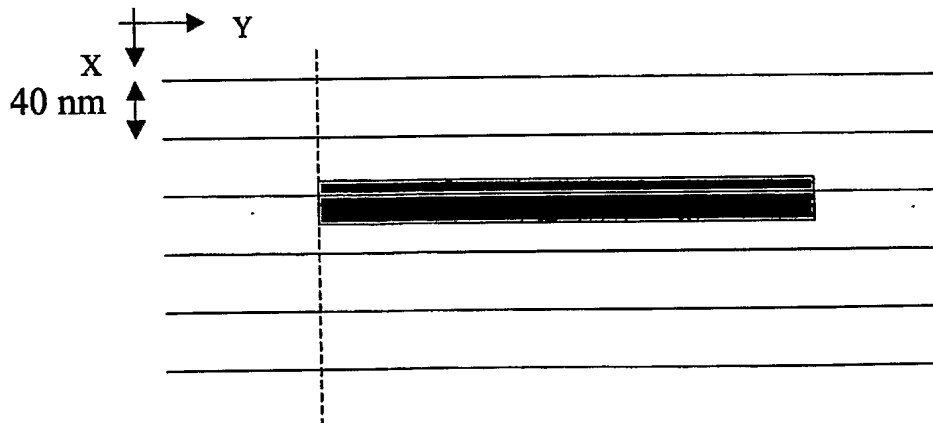
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When doing this "rotation" of the problem we need to re-calculate our parameters. In Y-direction our resolution was one measurement clock that corresponded to 292 nm. During one run over the pattern of interest we scanned it with a frequency of approximately 30 kHz. The question now is how far we move in X-direction between the scans. If we set the speed as low as possible we will retrieve about 8-10 scans of the pattern in each  $\lambda/2$  period. Since one  $\lambda/2$  period corresponds to 316 nm we have a resolution in the range of 30-40 nm in X-direction. This is because we scan the pattern with the frequency of 30 kHz during the movement in X-direction. Now when we use the  $\lambda/2$  signal as the reference we therefore have a "clock" with a spatial resolution of 30-40 nm in X-direction. This is significantly higher than the resolution in Y-direction. But! and this is important, we will not get as many samples in X-direction as in Y because of the movement in X. This fact is illustrated in next picture.



The situation in X-direction is shown in the picture below. A bar is scanned in one stroke (run) and generates one event only in the 6 scans. So when moving over the bar one time we know the position of the bar with an accuracy of  $\pm 40$  nm. The Y-coordinate of the bar location is known with the accuracy of  $\pm 292$  nm (in each of the two edges). In the picture above the CD in X-direction of the bar is lower than the 40 nm measurement grid we use in X-direction. So just running one time over the pattern might miss the fact that there is a bar at all.



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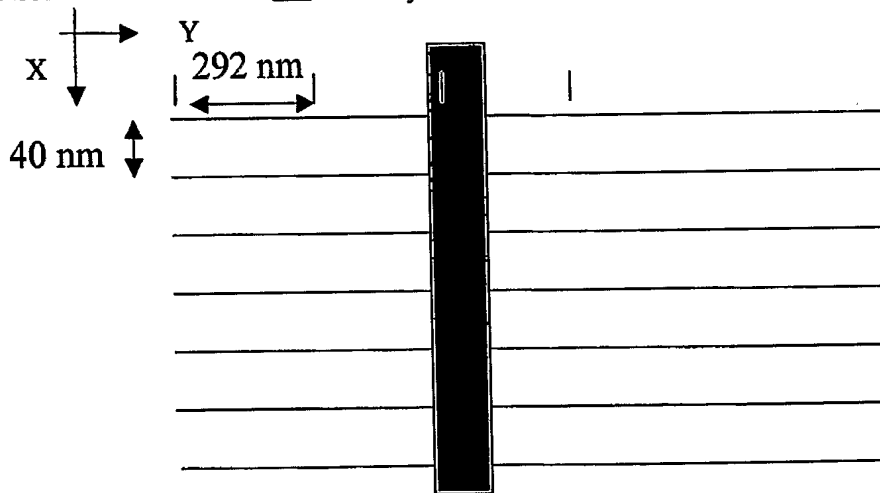
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This is natural since the resolution is lower than the CD of the bar to be measured. In order to measure the bar with higher resolution you need to do several runs over the pattern. If you compare the situation in Y-direction this can be illustrated in next picture.

Here you are scanning a bar with the same length in Y-direction. The resolution in Y-direction in each scan is 292 nm but you retrieve 7 scans over the same length of the bar.



If we separate the problem we can say that in one scan we can resolve a pixel with the resolution 40 nm in X-direction and 290 nm in Y-direction.



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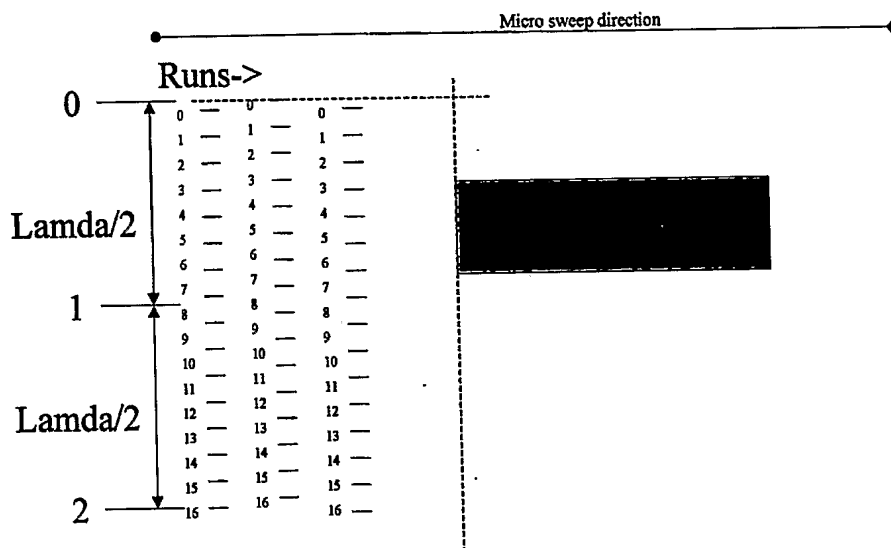
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**The algorithm.**

So far we have described the main principle in Y and X direction. We have rotated the problem in Y 90 degrees to X. In Y-direction we have two processes that are random relative each other. The measurement clock and the SOS (or any correlated signal to SOS). In X-direction the measurement clock corresponds to the SOS signal and the reference is the  $\lambda/2$  signal. Also these signals (or processes) are un-correlated. We have different resolution in the different directions but it turns out that the accuracy is almost the same. In next picture the principles of how to get the X-coordinate of a bar is described.



In the picture we see a bar that is parallel with the ruler. The reference signal is the  $\lambda/2$  positions. In each  $\lambda/2$  interval we scan the pattern with the micro sweep (our ruler). The travel over the pattern is done with a much lower speed compared to the speed used when exposing a pattern. In this example we get about 8 scans in the  $\lambda/2$  interval. If we now start to count SOS in the interval we will have a very similar situation as described above. If we count the total number of scans in the interval this will be a measurement of the speed in the interval. Since we cannot assume that the speed is the same in all the intervals it is important to do this speed calculation in order to get the correct "weight" of an event in the interval in X-direction. In this example we will get a Y-event (a transition from glass to chrome) when we have counted two SOS in the first run, three in the second and so on. So just adding the "index" of the event inside an interval and divide this number with total number of SOS in the interval will

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give us an estimation of the X-coordinate of an event inside a certain interval. Above we will get the approximate position of the first Y-event after three runs over the mark to be  $(2+3+2)/3 = 2.3$  SOS tics in the interval. To calculate what this corresponds to in nanometers we just multiply this number with the local resolution.

Here we get  $2.3 * 316/8 = 92.2$  nm. This is the local coordinate for the edge of the bar in the first interval. The local resolution depends on the speed, i.e. total number of SOS in the interval. If we can run the system more slowly this resolution will be better. But you will also gain resolution by scanning the bar in several runs. (Please refer to the appendix where the accuracy of the average position estimation is discussed).

As can be seen from above discussion we actually can calculate the X-coordinate from data retrieved from a scanning sweep in Y-direction. What we do is using the fact that we know exactly where we are in X-direction every time we pass an interval border. Inside an interval we only must assume that the speed is constant. This of course does not mean that the speed needs to be constant over all intervals. In practice we run several times across the pattern in both directions and record the Y-events and  $\lambda/2$  positions simultaneously. We therefore have the possibility to calculate the local speed with high accuracy by using information from all the runs.

**Filtering**

What we really are after is not the exact position of an individual pixel. The discussion so far has lead us to that single pixels position accuracy depends in how many times we have recorded the pattern and the resolution we use during the recording. If we scan the pattern a certain number of times we can "select" the accuracy we want before hand. This can be done since we have full control over the measurement process. When we do this "accuracy" selection we also must consider our cursors. As have been mentioned before a cursor is just another way to define number of pixels to use for calculating an average value.

There are many ways to apply a filter to this kind of data. An obvious way might be to fit a line using standard regression techniques. These techniques works but does not generates the optimum result in this case. The main reason is that the pixel data we handle does not describe a gaussian distribution. We have a more or less rectangular distribution to deal with. When using a regression technique we therefore will "over weight" pixels close to the border of a  $\lambda/2$  interval or the  $tm$  interval in the Y-case. A much better method to use is the more simple "area" estimation method. This method is also more accurate for this kind of data compared to the regression technique. To fit a line to an edge you just divide the database in two half's. In this case the data you have is x,y coordinates. You calculate the average value of all coordinates in each half. This way you will get two x,y points. These two points describes the line to be used in further calculations.



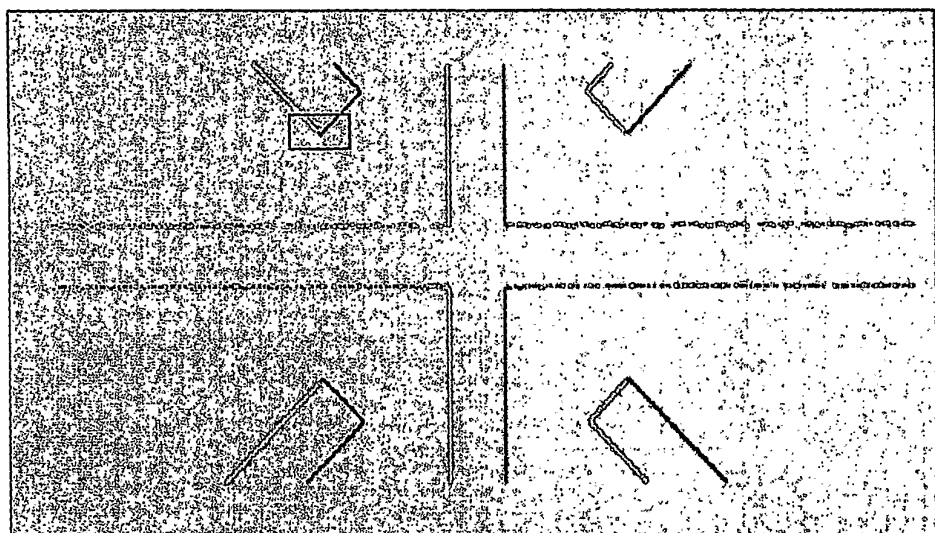
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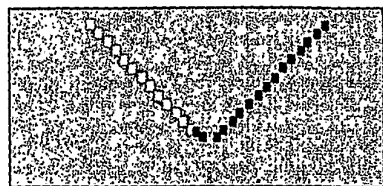
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**Some real results**

In next picture we have filtered the data using the above-described algorithm. So far we have not applied any cursors. Only the average locations of the pixels have been calculated. The image shown has been built from four runs over the mark.



The blue square in the image is enlarged in next picture.



Here we have used the algorithm and some filtering in order to "sharpen up" the data. Each pixel in this image is a result of all four runs over the pattern.

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## Registration calibration

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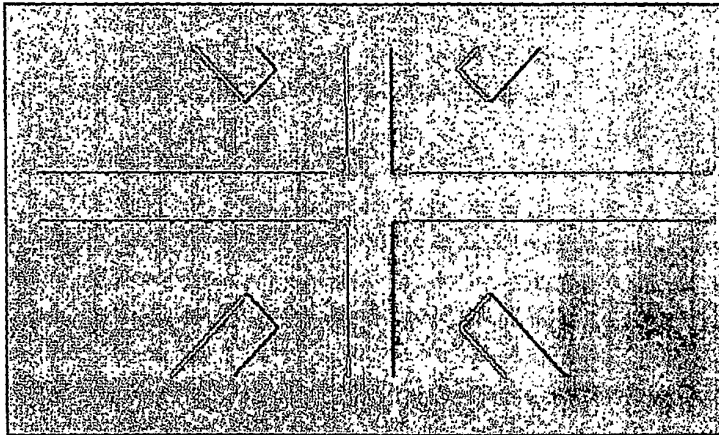
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### Cursors

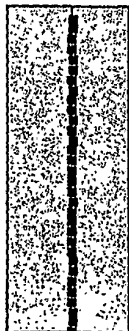
We now will apply cursors to the data in order to measure the CD and center of gravity position of the cross. The center of gravity of the cross is measured using four cursor pairs. These cursors are shown in next picture.



Each line of the cursors is calculated based on the data from the edge in the cross. The line is calculated by using the simple "area" estimation method described above. In below pictures a part of an X and Y bar is expanded.



This is a part of the upper left edge. The calculated cursor is an accurate estimation of the position of the edge in X-direction.



This is a part of the upper right edge of the cross. The position of this line defines the edge position in Y-direction.

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The reason for the mixture of white and black pixels along the Y-bar in the upper image above can be explained. The hardware has a limitation in that it can only re-trig on an event after two clock periods of the measurement clock. This means that if we have a positive and negative transition inside this time period we will miss one of the events. This is one of the reasons that the pixels are a bit spread in Y-direction. Then because of the noise the hardware will trig randomly on a negative or positive transition. This is actually no problem due to the fact that if we have a positive or negative transition is not so important information. What counts is where the transition occurs. To know the "direction" of the edge we can use several transitions or other kinds of logic decisions to know which type of transition we have.

In below table the center of gravity and the CD is presented for the cursors. Below table

File: f\_d\_f\_0602\_105508.sd Hw cursor: 99.22 um

Y-cursor 0

X0(um)	Y0(um)	X1(um)	Y1(um)	Centre(um)	CD(um)
38.843	---	53.380	---	46.111	14.537

Y-cursor 1

X0(um)	Y0(um)	X1(um)	Y1(um)	Centre(um)	CD(um)
53.348	---	38.789	---	46.069	14.558

X-cursor 2

X0(um)	Y0(um)	X1(um)	Y1(um)	Centre(um)	CD(um)
---	100.648	---	115.106	107.877	14.458

X-cursor 3

X0(um)	Y0(um)	X1(um)	Y1(um)	Centre(um)	CD(um)
---	100.690	---	115.128	107.909	14.439

shows the result of the four cursor pairs separately.

The center position of the mark (Xcenter,Ycenter) may be calculated as the average value of the Y-cursor center values (Xcenter) and the X-cursor values (Ycenter).

### Second order effects.

So far we have discussed the main principles of the algorithm. We will now discuss two vital corrections that must be done on the data that are second order effects from the method.

First we need to correct for an eventual azimuth angle in the data. If we use a writer (as done in this case) we have a pre-misalignment between the X-movement direction and the ruler. This angle (*Alpha*) can be expressed as:

$$\text{atan}(vx/vy)$$

Where *vx* is the exposure speed of the system and *vy* is the speed of the micro sweep.

This angle calculation can be reduced to the expression:

$$\text{Alpha} = \text{Number\_of\_beams} / \text{Sos\_rate}.$$



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Where the *Sos\_rate* is total number of pixel clock periods between two SOS. (Please look in the appendix for a more thorough explanation).

Another effect that must be taken care of is the effect of the X-movement during a measurement. Also here we will introduce an "azimuth" error. Even if we run the same number of positive strokes and negative strokes we will not cancel out this error completely. The reason is that this error has to do with the difference in speed for a positive and negative stroke. For a stroke in one direction we will therefore get an error that may be expressed as an angle (*Beta*).

This angle can be expressed as:  $Beta = xInc / speed * 1/(Sos\_rate * yPix)$  where *xInc* is  $\lambda/2$  [nm] and *speed* is total number of start of sweeps inside the *xInc* interval. If we divide

$Alpha = Number\_of\_beams / Sos\_rate$  with this angle we will get a relation between the angles.

$$Beta/Alpha = xInc/speed * 1/(nbeams*yPix)$$

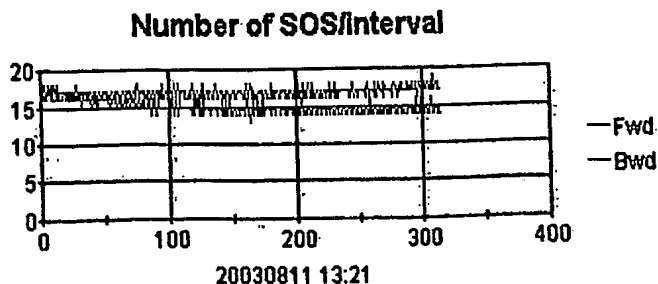
If we put in some realistic numbers, *xInc* = 316 nm, *Speed* = 8 *Sos*/interval, *nbeams* = 9 beams and *yPix* = 250 nm, we get:

$$Beta/Alpha = 316/8 * 1/(9*250) = 0.0175$$

If we calculate the error generated by *Alpha* on a distance of 100  $\mu$ m we will get:

$alpha\_error = 100 * 9 / 1435 = 0.6272$  nm. (The *Sos\_rate* is taken from TFT3 system parameters). Since the *Beta* = 0.0175 \* *Alpha* we can calculate the error generated by the fact that we are moving during measurement to be:

$0.0175 * 627.2$  [nm] = 11 nm. This is a quite large error that cannot be neglected. This error will change sign depending of the direction of the measurement. If we measure during the same number of positive and negative strokes and the local speed is the same for both strokes this error will be cancelled out completely. In practice this is not the case. We will therefore get a small net-error due to this fact. In the graph below the average speed is presented for a measurement. 2 Forward strokes and 2 backward strokes were used. The hardware cursor was 99.22  $\mu$ m (314  $\lambda/2$  intervals). As can



be seen there is a significantly difference in local speed for the forward and backward stroke.



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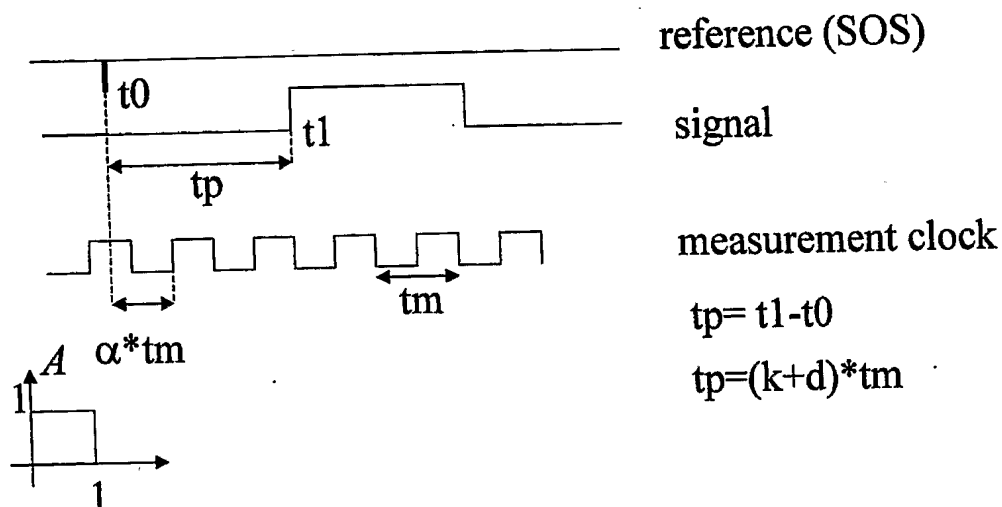
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## Appendix

### Random phase measurement.

When using a random clock for measurement we shall see this as a statistical problem. In below picture the measurement situation is illustrated. What we want to measure is the time  $t_p$  that is the difference between  $t_1$  and  $t_0$ . The signal is synchronized with the reference signal.



We re-write the time  $t_p$  as:

$$t_p = (k+d) * t_m$$

Where  $k$  is an integer number and  $d$  is the decimal part of  $t_m$ . If we do this  $d$  will be a number in the interval  $[0, 1]$ . It will be shown later why this is a reasonable expression to use for  $t_p$ .

We now introduce the measurement clock with a phase that is random relative the reference signal. We also introduce a counter that counts the positive going flanks of this clock. If we reset this counter with the reference signal we realize that we sometimes will count  $k$  flanks and some times  $k+1$  flanks. No other counts are possible. We introduce the discrete stochastic variable  $K$  that in this way can get two values  $k$  and  $k+1$ .

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We now look in the figure and introduce another stochastic variable,  $A$  which describes the phase of the clock relative the reference signal. A sample point of  $A$  ( $\alpha$ ) will be a number in the interval  $[0, 1]$ .  $A$  also is a continues stochastic variable  
If we now look in the figure again we see the following important facts:

If  $\alpha > d$  then the sample point of  $K$  will be  $k$ .  
If  $\alpha < d$  then the sample point of  $K$  will be  $k+1$

What we now must do is to calculate to probability for the sample point  $k$  and  $k+1$ . To do this we must use the frequency function shown in the picture above. Since all phases have the same probability this is a rectangular distribution function.

We have:

$$P = \int_0^d f(t) dt = d \quad (\alpha < d)$$

$$P = 1-d \quad (\alpha > d)$$

So the probability that we get the sample point  $k+1$  out from  $K$  will be  $d$  and the probability that we get the sample point  $k$  out of  $K$  is  $(1-d)$ .

When we add the clock counts for each measurement and then divide with  $n$  we actually is estimating the average value for the stochastic variable  $K$ .

The estimated mean value may be expressed as:

$$E(K) = \sum_{-\alpha}^{\alpha} k * p(k)$$

Here we have only two possible sample points so we get:

$$E(K) = k*(1-d) + (k+1)*d = k+d$$

So when we rescale this result to nano seconds we get  $(k+d) * tm = tp$ .

This result proves that building the average value of the counter tics and scale this value with  $tm$  will give us the time we are after.



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### The sigma

To calculate the accuracy of the average value  $E(K)$  we need to find the variance of  $K$ .  
The variance of a distribution may be expressed as:

$$V(K) = \sum_{-\infty}^{\infty} (k-m)^2 p(k) \quad (1)$$

This can be re-written as:

$$V(K) = E(K^2) - [E(K)]^2$$

We get:

$$V(K) = k^2(1-d) + (1+k)^2d - (k+d)^2 = d(1-d)$$

and

$$D(K) = \sigma = \sqrt{d(1-d)}$$

The variance function is actually very interesting. We see that if  $d=0$ , that means that we have no decimal part the  $V(K)=0$  we also see that if  $d$  is very close to 1  $V(K)=0$ . Actually the variance has its maximum when  $d=0.5$ . In this case the variance is 0.25. The sigma will therefore be 0.5 as its maximum.

To interpret this you may think as follows. If  $d$  is 0 we always will count  $k$  ticks from the counter. Here we also assume that we count one tick if the positive going edge from the clock coincides with the reference signal. Since we always is counting  $k$  ticks independently of the phase of the measurement clock the spread also from the average value will be zero since variance is a measurement of the squared distance from the estimated average value. (Please refer to "1" above).

What is then the physical meaning of this?

Let us first make a practical example.

If we measure a signal with the decimal part 0.01 and  $k=2$  the probability of counting a 3 in a measurement will be 0.01. This probability is the same for each measurement. Now if we calculate the average of 100 measurements we will probably add 99 samples of 2 and one sample of 3. But it is also possible that we add 100 samples of 2 and no samples of 3. The error we actually have in the average value is then:

$0.1 \cdot (1-0.1) / \sqrt{100} = 0.09 / \sqrt{100} = 0.009$ . So after 100 measurements in case 1 we will get  $(99 \cdot 2 + 1 \cdot 3) / 100 = 2.01 \pm 0.005$  and in the second case  $2.00 \pm 0.005$ .



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There is another very interesting way to see the physical conclusion of the case when  $d=0$ .

Assume that we want to measure a signal that is exactly  $k * tm$ . In this case the decimal part is zero. Now if we add counter ticks we must always count  $k$  ticks. Other vice, and this is important, we should never get the correct average that is  $k$  in this case. In other words we cannot ever count  $k+1$  ticks. If this would be the case the average we calculate would not be  $k$ . For this reasons the variance must be zero. Please note that only two numbers can generally be counted,  $k$  and  $k+1$ . So the value  $k-1$  can never be counted. So in other words a count that is  $k+1$  cannot be compensated by a value  $k-1$  so we get the correct average anyway.

Since we do not know  $tp$  beforehand we should use the worst-case scenario when we estimate the error. In other words we shall say that the error due to the method is:

$$Error(K) = 0.5 * tm [ns].$$

This is as shown above the maximum of the function  $d*(1-d)$ . If we want to use a symmetrical error instead we can express the method result as:

$$tp = (k+d) \pm 0.25 * tm [ns].$$

The error in the method will go down if we use a large number of measurements. We can express the error as:

$$measurement\_error = 1/\sqrt{n} * 0.5 * tm. [ns]$$

This expression can be scaled to nanometers as:

$$ErrorNm = 1/\sqrt{n} * 0.5 * rs [nm]$$

Where  $rs$  is the actual resolution for the actual direction. If we put in some numbers,  $rs=291$  nm in Y-direction and  $rs=40$  (316/8) nm in X-direction. So the error in the estimation of a pixel position in X or Y direction may be approximated to be:

$$YError = 1/\sqrt{n} * 145 [nm]$$

$$XError = 1/\sqrt{n} * 20 [nm]$$



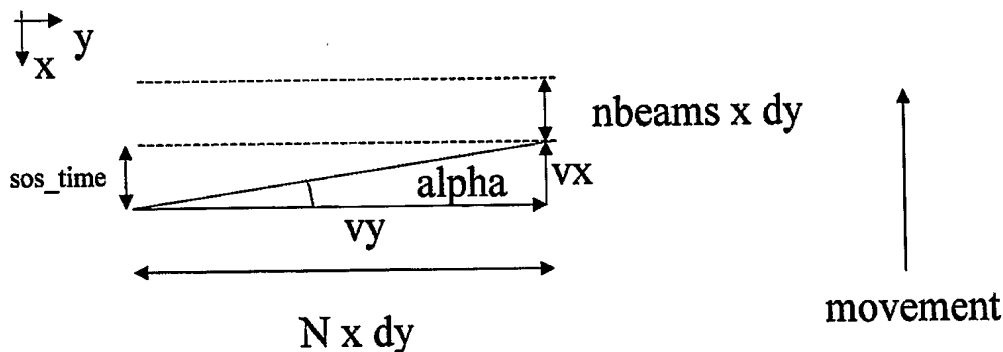
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### The azimuth angle

In below picture the exposure case is illustrated. Between two start of sweeps we moves the distance  $nbeams * dy$  [um] in X-direction.  $dy$  is the pixel size. We here assume a square pixel. In the same time we move  $N * dy$  [um] in Y direction.



$$vx = nbeams * dy / sos\_time \text{ [um/usec]}$$

$$vy = dy / pixel\_clock\_time \text{ [um/usec]}$$

$$sos\_time = N * pixel\_clock\_time \text{ [usec]}$$

The angle  $\alpha$  may be expressed as  $atan(vx/vy)$ . If we calculate this angle we get:

$$\alpha = atan( (nbeams * dy / sos\_time) / (dy / pixel\_clock\_time) )$$

The  $sos\_time$  may be expressed as  $N * pixel\_clock\_time$ .  $N$  is here the total number of pixels between two start of sweeps. Finally we therefore can express the angle  $\alpha$  as:

$$\alpha = atan(nbeams/N)$$

Please note that this angle is a constant "compensation" that must be removed from the database.